

## LA-UR-12-22256

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Title: Nuclear Fuel Cycle & Vulnerabilities

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Intended for: LANL Course: 2012 Nuclear Safeguards Technology & Policy Workshop



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# 2012 Nuclear Safeguards Technology & Policy Workshop

## June 18-22

## Nuclear Fuel Cycle & Vulnerabilities

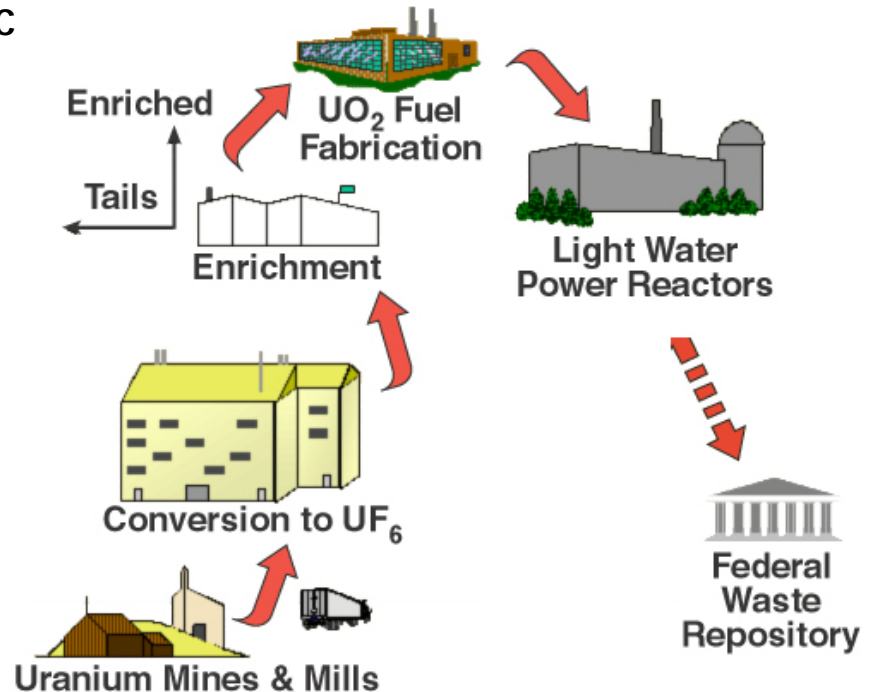


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Project Leader International Safeguards  
Nuclear Nonproliferation Division / N-4  
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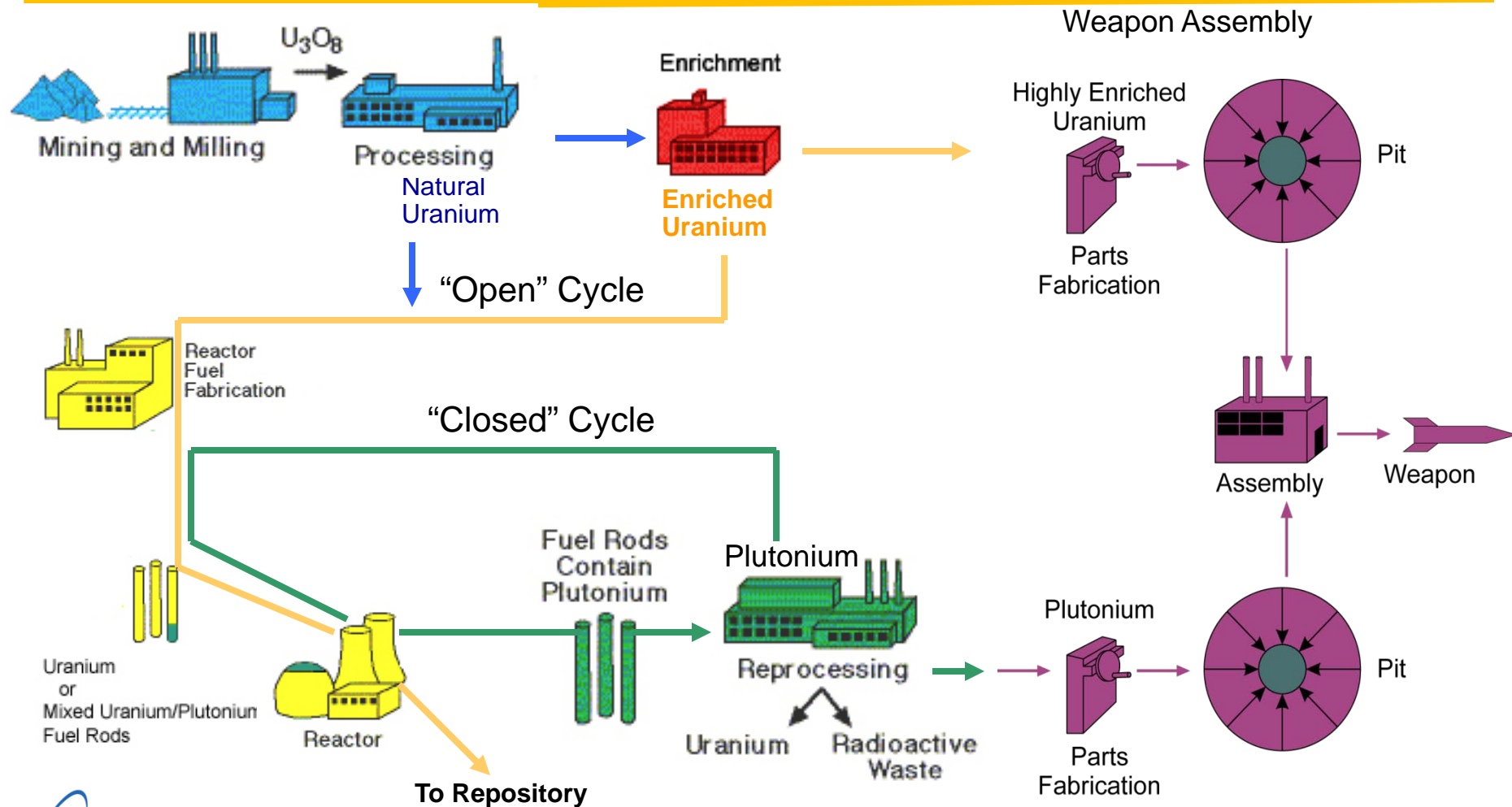
# Definition of the Nuclear Fuel Cycle

- Processes to obtain, refine, and exploit nuclear material for a specific purpose
  - Nat U, Th – Source material
  - $^{235}\text{U}$ ,  $^{233}\text{U}$ , Pu – Fissile Material
- There are several different types and subcategories
  - Power
  - Weapons
  - Naval Reactor Fuel
  - Radioisotope Production
  - Research
- Cycles also vary:
  - Degree of opportunity to obtain directly weapons-usable material
  - Degree of difficulty in safeguarding
  - Intertwining of the civil and military



**Example: The Open nuclear fuel cycle for power production in the United States**

# Civil and military fuel cycles overlap



# Mining

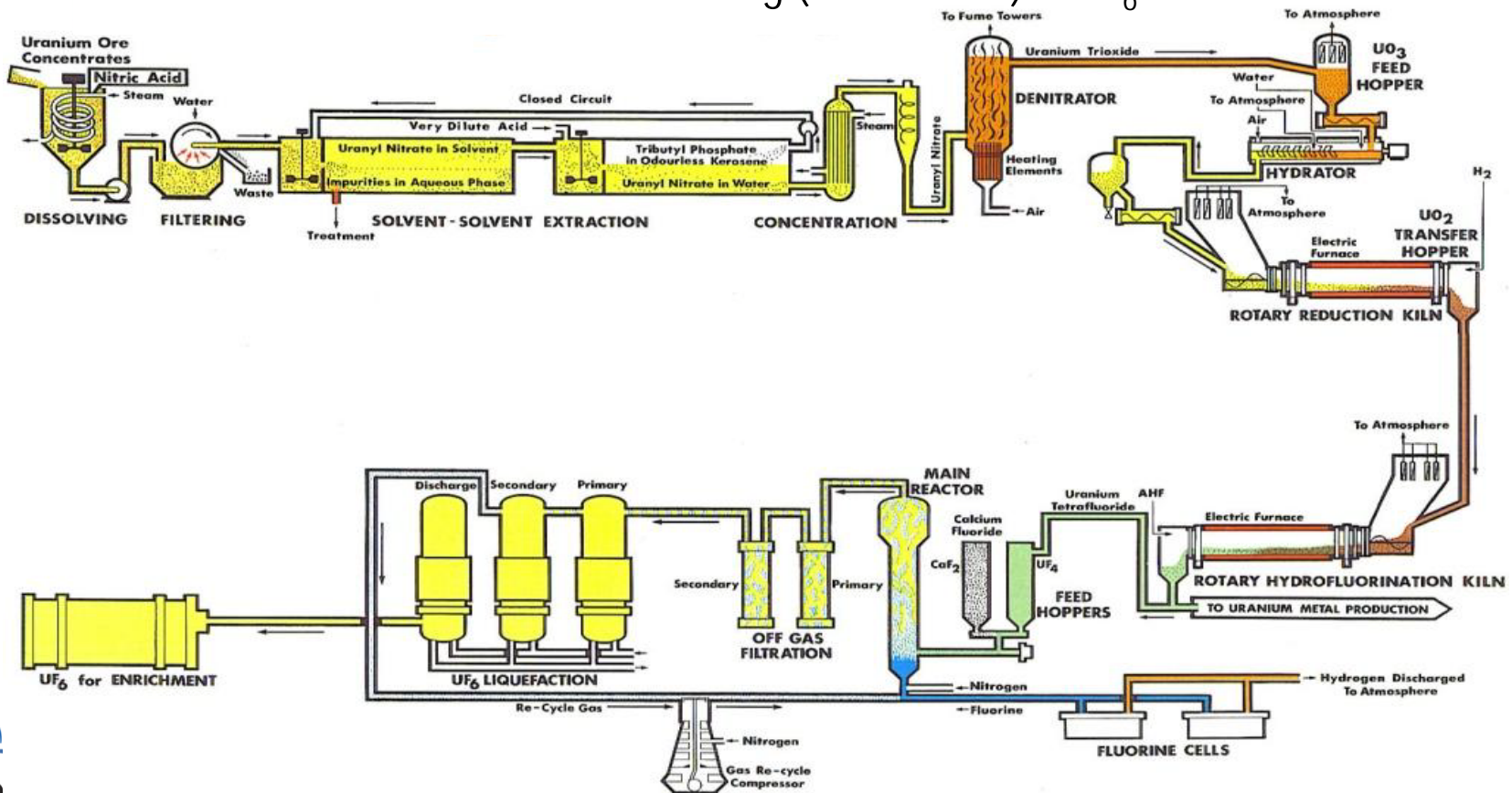
- Mining and Milling
  - Uranium
    - Key to fuel cycle of today
    - ...and near future!
  - Thorium - more abundant than Uranium
    - Thorium Fuel Cycle – never has taken off
    - Note large Resources in India



2009 Uranium Production (tU)	
Kazakhstan	14020
Canada	10173
Australia	7982
Namibia	4626
Russia	3564
Niger	3243
Uzbekistan	2429
USA	1453
Ukraine	840
China	750

# Conversion

- **Take Uranium Ore Concentrate and put into form for**
  - Nat Uranium Fuel or Further Processing (Enrichment) –  $\text{UF}_6$  Product



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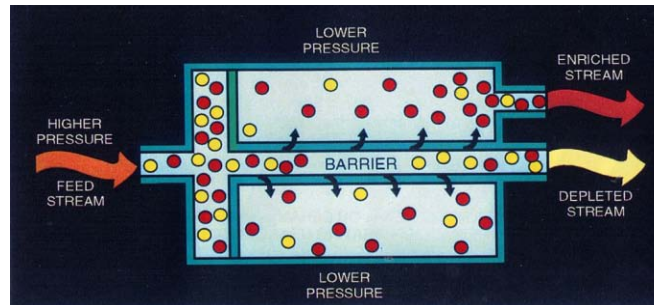
# Enrichment

- Various Historic Enrichment concepts

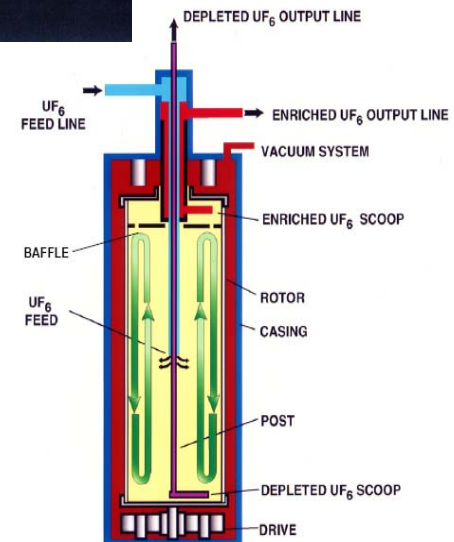
- EMIS



- Gaseous Diffusion



- Gas Centrifuge



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# Fuel Fabrication

- Fuel Fabrication
  - Natural Uranium
  - LEU
  - HEU
  - MOX
  - Th/<sup>233</sup>U
  - Fuel Forms
    - Metals
    - Oxides
    - Ceramics



# Reactors – All Classes

- LWR
  - PWR
  - BWR
  - VVER
  - Gen III / Gen III+
- On-Load
  - CANDU
  - RMBK
- Gas-Cooled Reactors
- Fast Reactors
- Breeders
- Gen IV
- Research Reactors and Critical Assemblies



Westinghouse PWR – Krško, SLO



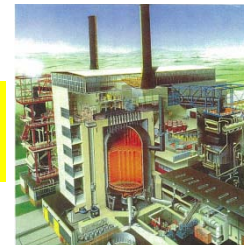
Loviisa WWER-440  
Finland



GE BWR Containment  
Shoreham, NY



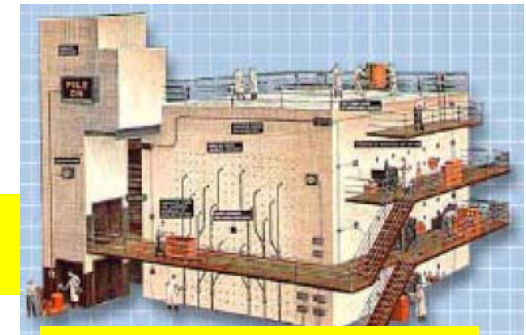
Chernobyl 4  
Ukraine



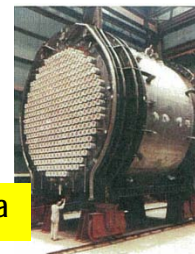
Calder Hall, UK  
Gas-Cooled 1950's vintage



Fresh Metal HEU Fuel  
Vinca - Serbia



Gas Graphite – BNL's BGRR



CANDU Calandria



Windscale and Calder Hall, UK

# Reprocessing

- History and controversy / Nonproliferation and safeguards
- PUREX and other aqueous techniques
- Electrochemical
- Future



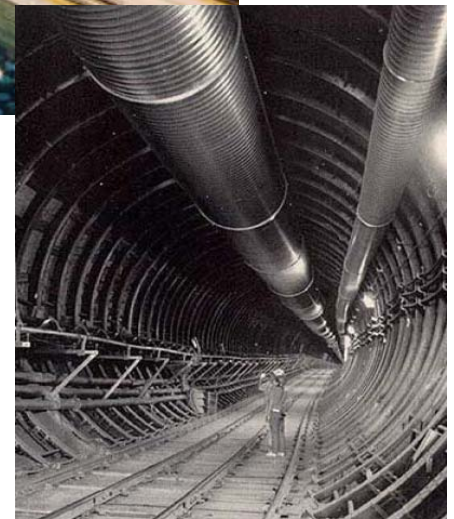
AREVA – La Hague Reprocessing Facility

DPRK – Reprocessing – Dr. Sig Hecker Visit



# Waste Disposal

- Spent Fuel Storage – short to medium term
- Geological Repositories



# Proliferation Challenges, Proliferation Indicators and Weaponization

- Proliferation challenges
  - Material Attractiveness
  - The Safeguards Technical Objective - INFCIRC/153 (Corr.) Para. 28:  
*... the objective of safeguards is the timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk of early detection...*
- Proliferation indicators
  - What makes you suspicious?
- Weaponization
  - The route

# Figure-of-Merit (FOM) for Material Attractiveness

- FOM<sub>1</sub> is a material property<sup>†</sup>
  - Measure of the attractiveness of material from the perspective of a Host State or sub-national entity with intentions to proliferate nuclear explosive devices:

$$FOM_1 = 1 - \log_{10} \left( \underbrace{\frac{M}{800}}_{\text{Size Factor}} + \underbrace{\frac{Mh}{4500}}_{\text{Stability Factor}} + \underbrace{\frac{M}{50} \left[ \frac{D}{500} \right]^{\frac{1}{\log_{10} 2}}}_{\text{Acquisition Factor}} \right)$$

*M*—bare critical mass in unpurified metal form (kg)

*h*—heat content in unpurified metal form (W/kg)

*D*—dose rate of 0.2·*M* @ 1 m (rad/h)

- FOM<sub>1</sub> bounds the range of nuclear materials that can potentially be processed and fabricated into a nuclear explosive device by an adversary
- Of use in determining proliferation resistance of a nuclear fuel cycle option

Source:

Charles G. Bathke, et al., "Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios," *Nuclear Technology*, Vol. 179, No. 1, July 2012, pp. 5-30.

# Relationship between Attractiveness Levels and FOM

FOM	Weapons Utility	Attractiveness	Attractiveness Level <sup>†</sup>
> 2	Preferred	High	~B
1-2	Attractive	Medium	~C
0-1	Impractical	Low	~D
< 0	Very Impractical	Very Low	~E

Source: <sup>†</sup>Bathke, et al., "An Assessment of the Attractiveness of Material Associated with Thorium/Uranium and Uranium Closed Fuel Cycles from a Safeguards Perspective," 2010. (LA-UR-10-04477 and LA-UR-10-03899)

- Attractiveness Levels<sup>†</sup> and FOM of nuclear materials—as defined by the Department of Energy (DOE)<sup>‡</sup>—are similar but not equivalent
- From a PR&PP perspective
  - Desirable FOM attractiveness designations are **Low** and **Very Low**
  - Undesirable FOM attractiveness designations are **High** and **Medium**
- There are benefits to developing processes that yield products with lower FOM values

Source and note: <sup>†</sup> "Nuclear Material Control and Accountability," U. S. Department of Energy manual DOE M 470.4-6 Chg 1 (August 14, 2006), <http://www.directives.doe.gov>.

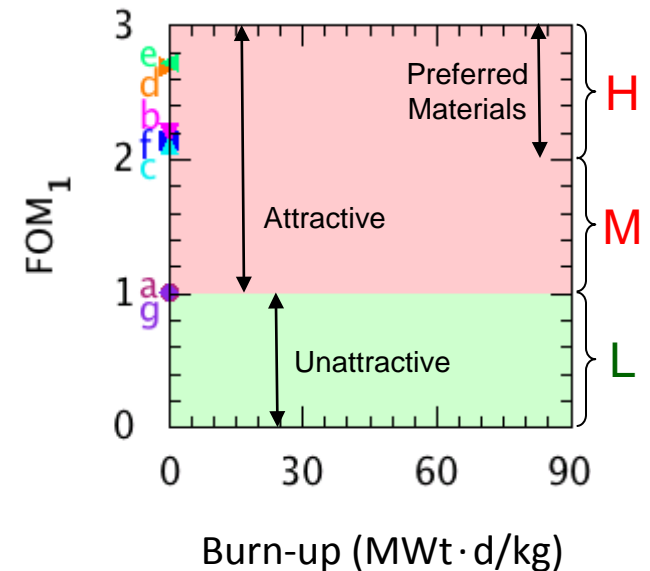
<sup>‡</sup> Depleted, Enriched, and Normal Uranium; <sup>233</sup>U; <sup>238</sup>Pu; <sup>239</sup>Pu; <sup>240</sup>Pu; <sup>241</sup>Pu; <sup>242</sup>Pu; <sup>241</sup>Am; <sup>243</sup>Am; Bk; <sup>252</sup>Cf; Cm; <sup>2</sup>H; Enriched Lithium; <sup>237</sup>Np; Th; <sup>3</sup>H; and Uranium in Cascades.

# Format of FOM Plots

- FOM<sub>1</sub> results shown for each case

Source:  
Charles G. Bathke et al., "Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios," *Nuclear Technology*, Vol. 179, No. 1, July 2012, pp. 5-30.

- The meaning of FOM values
  - FOM > 2 (red area): material is preferable for use in nuclear explosive devices
  - FOM > 1 (red area): material is attractive and should be safeguarded and secured
  - FOM < 1 (green area): material is unattractive, but may still be weapon usable
- The FOM values of seven common materials (delineated in the blue box below) are shown along the y-axis



a – LEU (20% <sup>235</sup>U)

c – <sup>237</sup>Np

e – WG-Pu (94% <sup>239</sup>Pu)

g – <sup>238</sup>Pu/<sup>239</sup>Pu (80:20)

b – HEU (93% <sup>235</sup>U)

d – <sup>233</sup>U (10 ppm <sup>232</sup>U)

f – RG-Pu

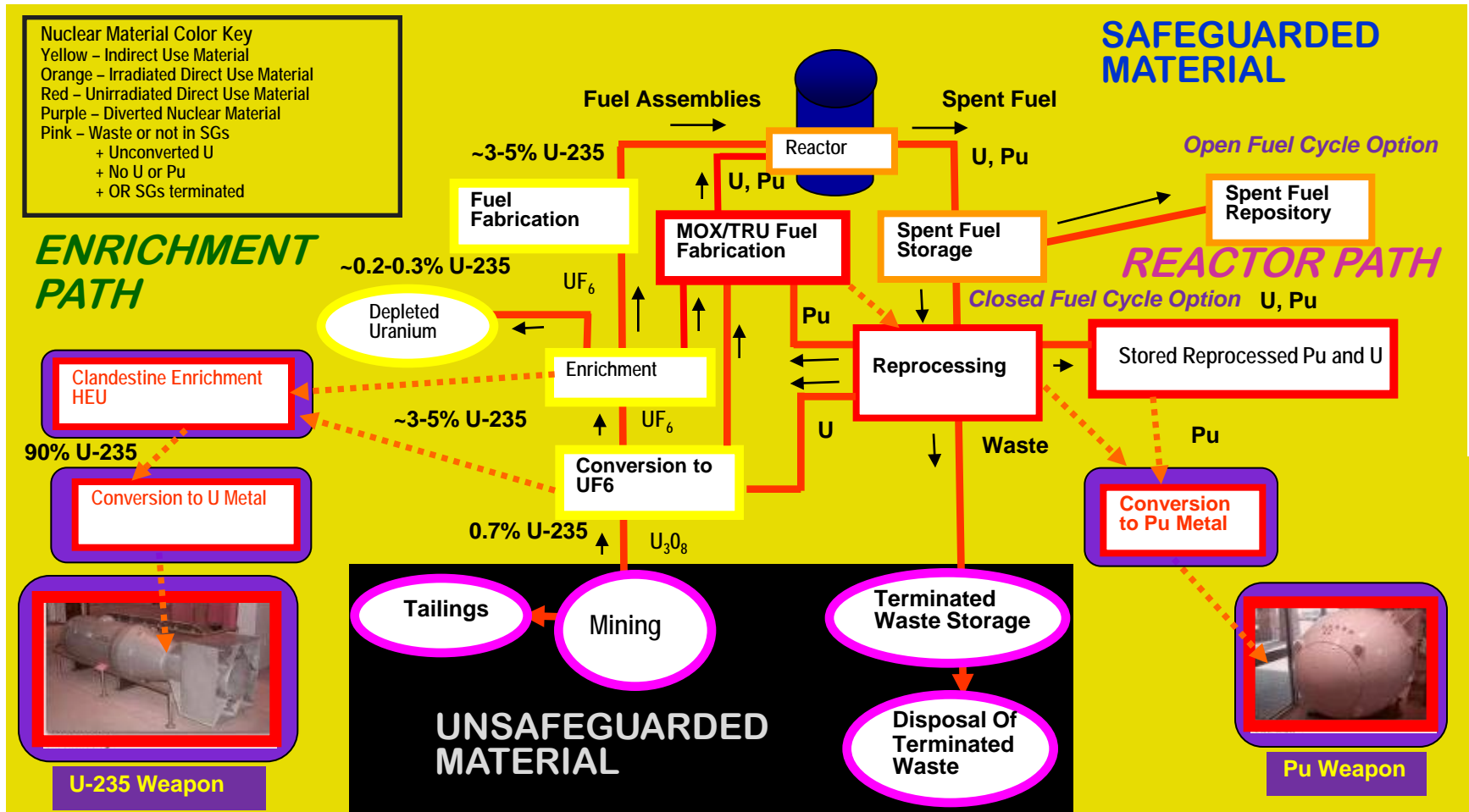
# Important Conclusions about Materials Attractiveness

- Plutonium is attractive for use in a nuclear explosive device
  - Co-extracting Pu with other actinides does not render an unattractive product
  - Co-extracting Am with Cm does produce a product that is unattractive
- Addition or dilution can render Pu or a TRU mixture unattractive
  - Pu + U  $\rightarrow$  80%  $^{238}\text{U}$  concentration
  - TRU + U  $\rightarrow$  75%  $^{238}\text{U}$  concentration
  - TRU + Ln  $\rightarrow$  >20% of all Ln in SNF

*Source:*

Charles G. Bathke, et al., "Attractiveness of Materials in Advanced Nuclear Fuel Cycles for Various Proliferation and Theft Scenarios," *Nuclear Technology*, Vol. 179, No. 1, July 2012, pp. 5-30.

# The Fuel Cycle with Safeguards Aspects



# Objectives of International Safeguards System

- “The safeguards system should be designed to provide credible assurances that there has been
  - no diversion of declared nuclear material
  - no undeclared nuclear material and activities ”

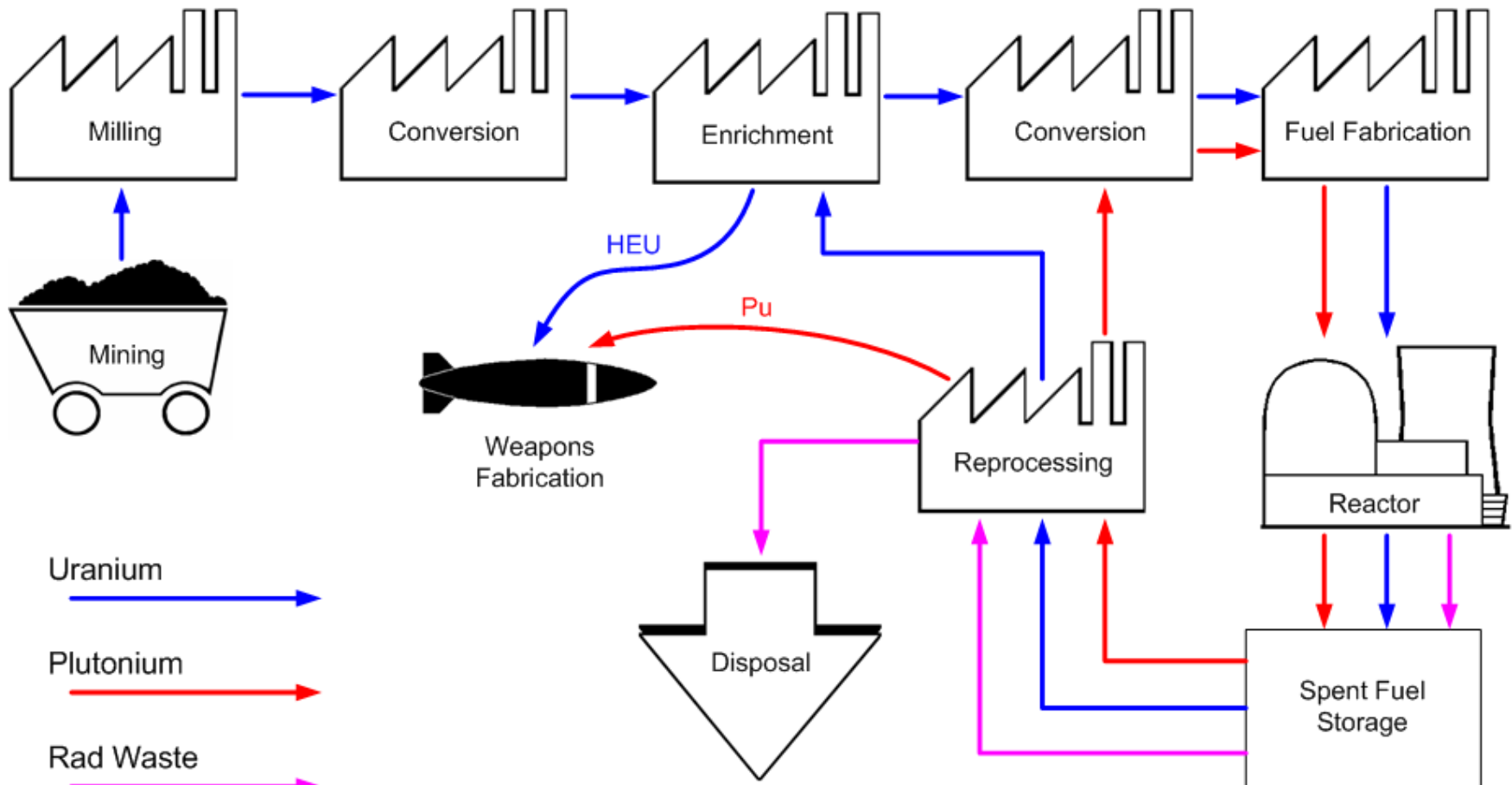
*(IAEA Board of Governors, March 1995)*



*How can we detect proliferation?  
What proliferation indicators?*



# Plutonium and High-enriched Uranium Could Be Diverted



From Fred Wehling, MIIS

# Proliferation Pathway Analysis

- Consider the Nuclear Fuel Cycle
- Consider weaponization activities required to successfully produce & deliver nuclear weapon
- Analyze State to determine which components are present or missing

		Detectability (Selected Criteria)		
		Identifiable Structure	Thermal Signature	Effluents
Plutonium Production	Reactor	Yes	Yes	No
	Reprocessing	No	No	(Yes)
Uranium Enrichment	Calutron/EMIS	No	Yes	Yes
	Gaseous diffusion	Yes	Yes	Yes
	Centrifuge	No	No	No

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# Proliferation Pathway Analysis

## Critical Technologies

- **Fissile Nuclear Material (NM) production & handling**
  - Uranium (U) enrichment & facilities with isotope separation capabilities
  - Plutonium (Pu) production reactors
  - Pu separation & purification (**reprocessing**), metallurgy
  - Criticality & health physics

Source:

*Nuclear Proliferation and Safeguards: Appendix Volume II, Part Two*

June 1977

OTA-BP-ENV-177 NTIS order #PB-275843 GPO stock #052-003-01360-6

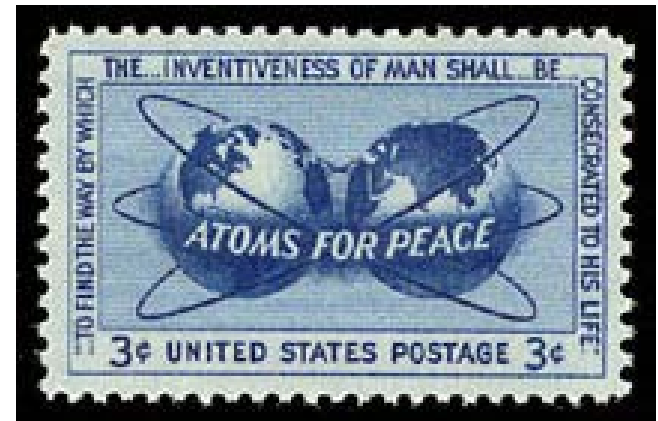
(John Lamarsh – consulted at BNL)

# Weaponization of the Atom

- The path to weapons
  - Plutonium Path



- Uranium Path



- Atoms for Peace Conundrum



# Proliferation Pathway Analysis Weaponization Technology

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- **Weaponization**
  - Integrated computational modeling
  - Fissile metal part fabrication
  - Electronic fire-sets, fusing/detonation, high explosives testing, modeling, delivery vehicle development, nuclear testing, ...

# History of Manhattan Project

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- What can be learned 70 years later?
  - It had no assistance – start from scratch
  - It was comprehensive
  - It is well documented
  - It worked

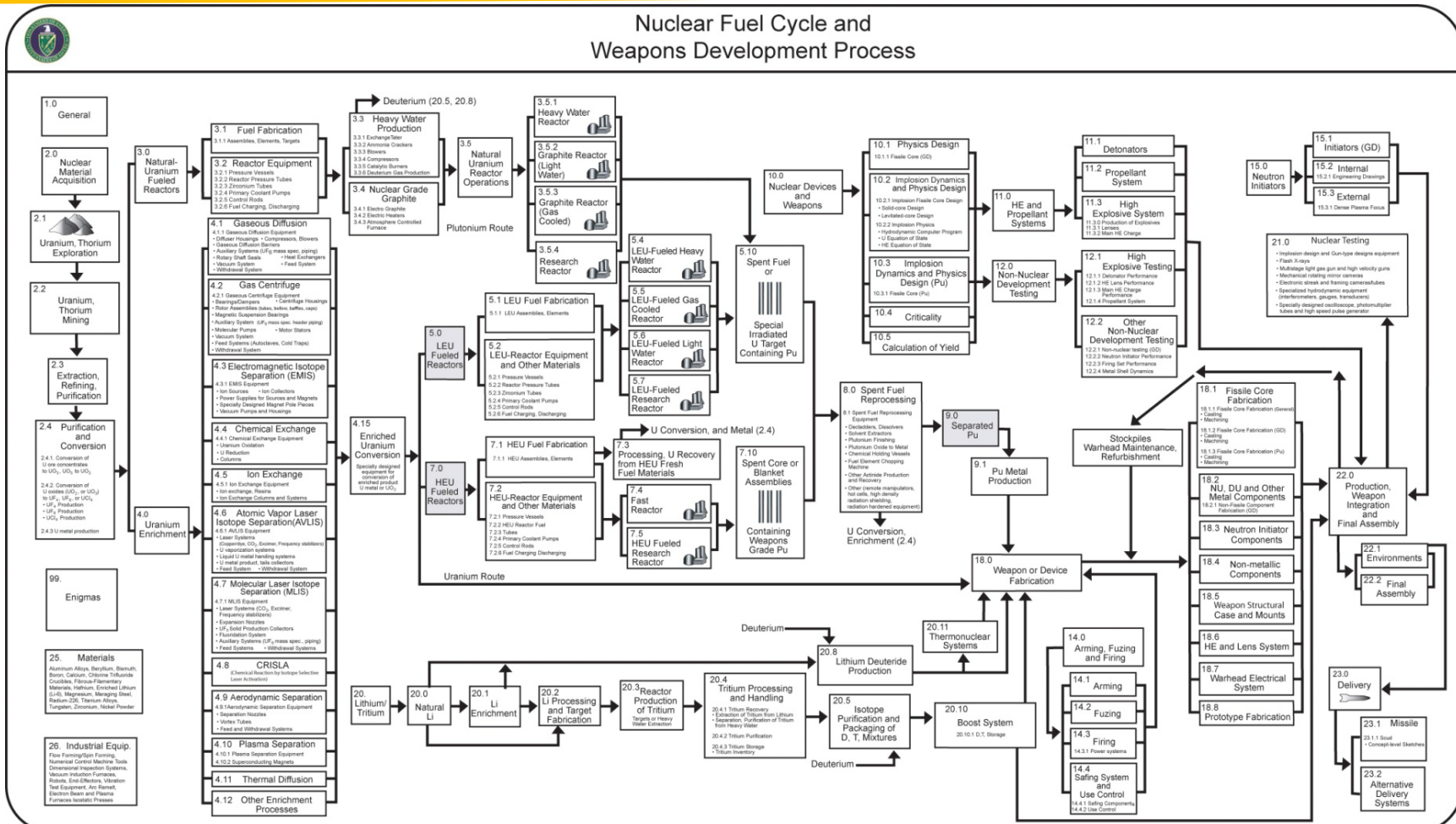
# Lessons of Manhattan Project

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- Good Program leadership
- Quality senior staff
- Large number of qualified staff
- Large industrial base
  - Indigenous – P-5 – Industrial Powers (G8 – G20)
  - Foreign suppliers – Khan network
- Safety
- Security
- Finance
- Political Will
- Time

# Nuclear Fuel Cycle

## With Weapons Development Process



Prepared by Pacific Northwest National Laboratory

Chuck E. Wilingham (509) 372-4159

12 Nov 2004

# R&D Analysis

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- Look for trends and patterns in R&D
  - Not just topical research
- Need to build databases of
  - Topics
  - Authors
  - Affiliated individuals
  - Institutions
- Look for relationships and patterns over time

# Civil Nuclear Energy and Proliferation

## (Dual-Use Dilemma) (Technical Cooperation vs. Safeguards)

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- Reactors used to produce energy or for research
  - Produce plutonium that could be used in nuclear explosives
- The same facilities used to enrich uranium or reprocess plutonium for peaceful purposes can be used to produce material for nuclear weapons
- Undeclared or secret nuclear fuel cycle facilities could also be used for this purpose
- Essential equipment lists for facilities – helpful
- Key concern: training in nuclear skills migrates to weapons
  - Nuclear, Chemical, Electrical, Engr., Nuclear Physics

# Conclusions

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- Nuclear fuel cycle has complexities and vulnerabilities
- Material Attractiveness - Key Lessons
  - Plutonium is attractive for use in a nuclear explosive device
    - Co-extracting Pu with other actinides does not render an unattractive product
    - Co-extracting Am with Cm does produce a product that is unattractive
  - Addition or dilution can render Pu or a TRU mixture unattractive
- Proliferation Indicators
  - Plutonium path – reactors + reprocessing
  - Uranium path – enrichment
- Reactor Technology can be a gateway for proliferation
- Small scale lab activities can be clue to larger clandestine efforts